Int J Life Cycle Assess (2012) 17:904–918
DOI 10.1007/s11367-012-0423-x

SUSTAINABLE DEVELOPMENT

Lights and shadows in consequential LCA

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Received: 6 December 2011 / Accepted: 28 March 2012 / Published online: 24 April 2012

Abstract
Purpose Consequential LCA (CLCA) is becoming widely used in the scientific community as a modelling technique which describes the consequences of a decision. However, despite the increasing number of case studies published, a proper systematization of the approach has not yet been achieved. This paper investigates the methodological implications of CLCA and the extent to which the applications are in line with the theoretical dictates. Moreover, the predictive and explorative nature of CLCA is discussed, highlighting the role of scenario modelling in further structuring the methodology.

Methods An extensive literature review was performed, involving around 60 articles published over a period of approximately 18 years, and addressing both methodological issues and applications. The information was elaborated according to two main aspects: *what for* (questions and modes of LCA) and *what* (methodological implications of CLCA), with focus on the nature of modelling and on the identification of the affected processes.

Results and discussion The analysis points out that since the modelling principles of attributional LCA (ALCA) and CLCA are the same, what distinguishes the two modes of LCA is the choice of the processes to be included in the system (i.e. in CLCA, those that are affected by the market dynamics). However, the identification of those processes is often done inconsistently, using different arguments, which leads to different results. We suggest the use of scenario modelling as a way to support CLCA in providing a scientifically sound basis to model specific product-related futures with respect to technology development, market shift, and other variables.

Conclusions The CLCA is a sophisticated modelling technique that provides a way to assess the environmental consequences of an action/decision by including market mechanisms into the analysis. There is still room for improvements of the method and for further research, especially in relation to the following aspects: clarifying when and which market information is important and necessary; understanding the role of scenario modelling within CLCA; and developing a procedure to support the framing of questions to better link questions to models. Moreover, we suggest that the logic of mechanisms could be the reading guide for overcoming the dispute between ALCA and CLCA. Going further, this logic could also be extended, considering CLCA as an approach—rather than as a modelling principle with defined rules—to deepen LCA,

Responsible editor: Mary Ann Curran

Electronic supplementary material The online version of this article (doi:10.1007/s11367-012-0423-x) contains supplementary material, which is available to authorized users.

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providing the conceptual basis for including more mechanisms than just the market ones.

Keywords Affected processes · Ceteris paribus assumption · CLCA · Consequential LCA · Framing the question · Market mechanisms · Scenario modelling

1 Introduction

Consequential LCA (CLCA) is a modelling technique whose applications have boomed in the last 4 years in the scientific community (Fig. 1). Introduced in the 1990s (Weidema 1993), the topic has been elaborated mainly in the last decade (Curran et al. 2005; Ekvall 2002; Ekvall and Weidema 2004; Ekvall et al. 2005; Tillman 2000; Weidema 2003). An important reference in this field is the work by Ekvall (2002), according to which CLCA was defined as aiming "at describing the effects of changes within the life cycle" (p. 403), where "changes" to some parts of the life cycle inventory system led to a series of consequences through chains of cause–effect relationships (Curran et al. 2005). Subsequently, more complete definitions were formulated, according to which "the consequential approach to life cycle inventory attempts to estimate how flows to and from the environment will change as a result of different potential decisions" (Curran et al. 2005, p. 856). On the same line, CLCA was defined as aiming at "describing how the environmentally relevant physical flows to and from the technological system will change in response to possible changes in the life cycle" (Ekvall and Weidema 2004, p. 161). Many other definitions were given, enriched over the years to highlight the market-oriented nature of the model. In fact, the term "marginal and market-oriented" was used by Nielsen and co-workers (Nielsen et al. 2007; Nielsen et al. 2008; Nielsen and Hoier 2009) to denote an approach in which "environmental profiles are compiled by addressing changes induced by a change in demand for the company's products, and co-product issues are handled by system expansion" (Nielsen et al. 2007, p. 433). Schmidt and Weidema (2008) and Schmidt (2010) further refined the definition, introducing the concept of a consequential approach to system delimitation as that in which "the actual affected suppliers and technologies are modelled instead of averaged. In addition, co-product allocation is avoided by system expansion" (Schmidt 2010, p. 183).

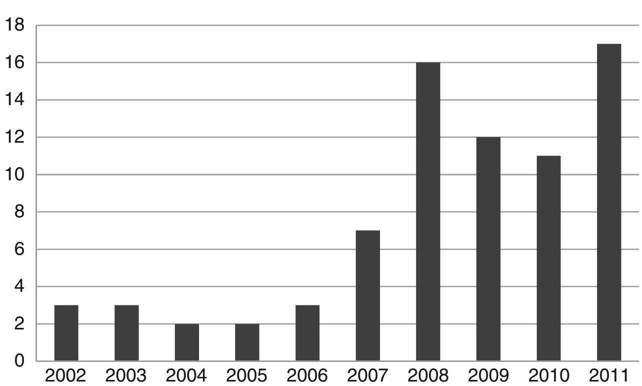

Fig. 1 Histogram of the number of articles published from 2002 to 2011 which contain the word "consequential" AND "LCA" in their abstract, title or keywords. The *diagram* shows in particular an increase in the number of publications on CLCA from 2007 on

Each definition built on a previous one, trying to add new elements to clarify the concept at a methodological level, and preparing the road for case studies. These started almost in parallel with the methodological development, but gained their momentum around the middle of what Guinée et al. (2011) defined as the decade of elaboration in LCA (2000–2010).[1] CLCA has been applied to a wide range of products (e.g. Astrup and Fruergaard 2011; Geyer 2008; Kimming et al. 2011a, 2011b; Nguyen et al. 2010; Schmidt et al. 2007; Thrane 2006), and also outside LCA, with the introduction of the concept of consequential social life cycle assessment[2] (Jörgensen et al. 2010). A clear example of a CLCA study is provided by Ekvall and Andrae (2006) who analyse what would happen if, after the ban on lead in solder pastes used in the electronics industry, the production would shift from SnPb to Pb-free solder. The consequences analysed refer to the fact that the solder shift increases electricity use, especially in the solder application. This means that less electricity will be available for other purposes. These dynamics require the use of partial equilibrium models to be solved, and thus the information about the sensitivity of the supply and demand of lead and scrap lead to price fluctuations.

There are also plenty of examples of CLCA applied to biofuels (e.g. Hedegaard et al. 2008; Melamu and Blottnitz 2011; Reinhard and Zah 2009, 2011; Silalertruksa et al. 2009). In that context, CLCA was used to address problems like the environmental consequences of the production of second-generation biofuels compared to current palm oil biodiesel production (Lim and Lee 2011), and to investigate the likely indirect effects of the development of a grass biomethane industry in Ireland, such as a reduction in beef exports to the UK (Smyth and Murphy 2011). Indeed, the debate on biofuels and on other bio-based products contributed to the speeding up of the methodology, particularly in relation to the effects of land use change. The seminal study by Searchinger et al. (2008)

[1] The decade of elaboration makes reference to a period characterised by the development of multiple different approaches, ranging from dynamic LCA to spatially differentiated LCA, and environmentally extended input–output based LCA, to mention just a few.

[2] A consequential social life cycle assessment would take into account not only social impacts on the stakeholders in the life cycle, but also those related to the non-implemented product life cycle (i.e. when not carrying out a process or using a product).

found that most of the previous LCA studies provided only a limited answer to the problem. In fact, by excluding emissions from land use change, they failed to account for the indirect effects (i.e. those taking place outside the biofuel value chain). Indirect effects, which may be quite relevant, are those that result, for example, from the competition between food and fuel (the land currently used for food can be allocated to fuel production), or from the competition for limited biomass in general, including competition between alternative energy uses for biomass (Hedegaard et al. 2008). Thus, replacement/displacement mechanisms started to be analysed and approaches to include them in LCA have been proposed.

Considering the increasing interest in CLCA within and outside the LCA community, and the potential of the approach, we have analysed the methodological implications of CLCA. Our research questions were: what is CLCA exactly? For what is it useful? How is CLCA perceived and used among practitioners? To what extent have the applications carried out so far been in line with the theoretical dictates, in particular, with reference to the way in which affected processes are identified and multi-functionality is dealt with?

The analysis builds upon previous reviews (Earles and Halog 2011; Finnveden et al. 2009; Reap et al. 2008; Zamagni et al. 2008), further broadened and updated, and addresses both methodological papers (22 articles) and applications (38 articles) that have been published over a period of 18 years. While the details of the literature review are available in the Electronic Supplementary Material, this article discusses two key issues derived from the review: "what for" and "what". In other words, for which applications has CLCA been used (and thus, which questions have been answered in the scientific literature by CLCA), and what is CLCA? A direct comparison between CLCA and attributional LCA (ALCA) is out of the scope of this article, as this issue has been widely debated in the scientific community (see for example Ekvall et al. 2005) and such a discussion would just perpetuate the myth that only one way to conduct LCA is correct. The analysis conducted in this paper is centred on CLCA.

Starting from the debate occurred in the past and elaborating on it, Section 2 focuses on the "what for" ("Questions and modes of LCA"), while Section 3 discusses the "what" ("Methodological content of CLCA"), with focus on the nature of modelling and on the identification of affected processes. Finally, a discussion and structure of the main findings is provided in Section 4, and conclusions are summarized in Section 5, where recommendations for further research are also provided.

2 "What for"—questions and modes of LCA

Which type of life cycle inventory modelling to adopt and for which purpose is a question that has been debated for 20 years (Tillman 2000) but the dispute is not yet solved. This is a critical aspect, because a correct application of the method is strictly related to the identification of the problems for which it provides the best answer(s), as also pointed out by several authors (Frischknecht and Stucki 2010; Guinée et al. 2002; Tillman 2000), and recently in other fields, such as Risk Assessment (Kapustka et al. 2010). However, its importance continues to be neglected.

Different modes or types of LCA have been identified, which represent attempts to capture the notion that LCA can be conducted in a variety of ways. Guinée et al. (2002) introduced two modes of LCA, descriptive and change-oriented (which echo attributional and consequential), and three types of questions, related to three main types of decisions: occasional (one-off fulfilment of a function), structural (related to a function regularly supplied), and strategic (related to function supplied for a long or even indefinite period). Four decision-context situations are identified in the ILCD Handbook (EC JRC-IES 2010), namely micro-, meso/macro-levels, and two modes, ALCA and CLCA. Their application is guided by specific LCI method approaches to allocation or system expansion/substitution. Together with ALCA and CLCA, Frischknecht and Stucki (2010) introduced decisional LCA (DLCA), based on future actual or anticipated economic and/or contractual relation. Moreover, the authors also propose the (economic) size of the object of investigation as a criterion for choosing among the different modes of LCA.

On top of this, Guinée and Heijungs (2011) recently suggested that another mode of LCA might be relevant to explore: back-casting LCA (BLCA), a scenario-based way to model specific product systems to normative future targets. In CLCA, global consequences in terms of CO_2, land, water, and resource uses, among others, are all modelled from a single product's perspective. Indeed, although CLCA is particularly suitable for mapping the impacts of processes indirectly affected by a decision, simply summing up all single product CLCAs does not necessarily result in sensible estimations of global consequences. Guinée and Heijungs (2011) therefore argue that we may consider exploring ways to back-cast normative targets for CO_2, land, water, and resource uses to global scenarios for agriculture, energy production, and transport (cfr. Graedel and van der Voet 2010), and to relevant LCA scenarios (e.g. from the global 2050 IPCC target of 450 ppm CO_2-eq. to global energy and transport scenarios—being the highest contributors—to single product's consequences).

However, the distinction between A (attributional), B (back-casting), C (consequential) and D (decisional) LCA does not seem sufficient for properly supporting practitioners in understanding which questions could be better answered by which mode of LCA. Over the last 15 years, many authors have been discussing the knowledge generated by LCA,

especially with reference to CLCA and ALCA. Ekvall et al. (2005), and Sandén and Kalström (2007) state that both ALCA and CLCA can be applied for modelling future, past, or current systems. Others (e.g. Lundie et al. 2008; Tillman 2000) recommend the use of CLCA for decision-making, while others consider CLCA as the method able to generate the most relevant information, independently of the application. The reason is that LCA is considered interesting and relevant only if it affects decisions and, in turn, a rational decision-making requires information about the consequences of the decision (Wenzel 1998). Along the same line of thought, Weidema (2003) recognises the relevance of CLCA in most of the decision-context situations, with the exception of a few cases (e.g. studies on environmental taxation) in which the ALCA could be considered more appropriate. Moreover, he considers ALCA relevant also when no specific decision is at hand for increasing the understanding of the causal relations within the product chain, and between this chain and the surrounding technological system. Finally, Lundie et al. (2008) suggest avoiding CLCA when the difference between the CLCA and ALCA results is small, and when the uncertainties in modelling outweigh the insights gained from it. This suggestion is questionable since the difference in results and the degree of uncertainty are not generally known until both methods are applied.

Overall, what emerges from the discussion above is that there is not a right or wrong mode in which LCA can be carried out, both ALCA and CLCA have utility. The difference consists in how boundaries are defined, which stems from a clear and unambiguous definition of the goal of the study. In fact, as already recognised by other authors (e.g. Curran et al. 2005; Ekvall et al. 2005; Tillman 2000), confusion arises in understanding the usefulness of CLCA because the questions to be answered are not formulated in a clear way.

Usually, the purpose of the study is defined, but this is not enough to decide whether or not to use CLCA. Table 1 and Table 2 report some examples of questions formulated in the literature for which a CLCA modelling was applied, together with the identification of the consequences addressed and the target audience of the study.

The examples in Table 1 refer mainly to case studies carried out in the "LCA context", i.e. either published in journals in which LCA has a prominent role or conducted by practitioners with notable experience in LCA.

Simply stating that the purpose is to evaluate the potential environmental impacts associated with the production of *X* (e.g. Gamage et al. 2008; Lesage et al. 2007b; Nielsen et al. 2007; Nielsen and Hoier 2009), or to investigate whether a technology is a more environmentally sound alternative than a conventional way of producing a particular product (e.g. Skals et al. 2008) still leaves the modelling choices open to a number of interpretations.[3] Moreover, the concept of consequences is never mentioned in the purpose of the study and the authors seldom explain why a consequential modelling has been selected instead of an attributional or decisional one. A reason could be that in many cases the application of CLCA was just the purpose and not the means of the study. An explanation for that could be that since CLCA is a new modelling approach, most applications have focused on testing the method in order to understand how it works and whether it gives different results compared to ALCA (e.g. Ekvall and Andrae 2006; Gaudreault et al. 2010; Thomassen et al. 2008).

Table 2 focuses on examples concerning biofuels and it shows a different situation with respect to Table 1. In fact, the questions of the studies are formulated in a clearer way, and refer mainly to research problems analysing decisions which have consequences at the macro level (whole economy or country level). It seems that the consequential approach is better understood when applied at a higher level of the analysis than the product one, like the examples in Table 1. This would be in line with the provisions of the ILCD Handbook, according to which a consequential modelling is suggested when large-scale consequences are involved. The typical decision context is that of policy development/information, in which the decision and the related changes "will affect the rest of the economy by having large-scale structural effects" (EC JRC-IES 2010, p.40).

Reinhard and Zah (2009) for example examine the consequences expected in Switzerland if 1 % of the current diesel consumption were replaced with imports of soybean methyl ester or palm methyl ester. Silalertruska et al. (2009) analyse the effects that would occur at the global level if cassava demand increased in Thailand, while Smyth and Murphy focus on the effect at country level. In both Table 1 and Table 2, the target audience is not always made clear, even if in most cases it can be easily identified. This is another aspect that hampers the correct identification of the most appropriate modelling approach to the research questions at hand. In fact, a complete and detailed definition of the decision context is fundamental in determining the most appropriate methods for the modelling, besides affecting also other key aspects of the scope definition (EC JRC-IES 2010).

This lack of clarity about CLCA is also due to the ambiguous interpretation of the definition and the concept given by practitioners. Starting from the most quoted definitions (Curran et al. 2005; Ekvall and Weidema 2004;

[3] It is worthy to note that stating the purpose of the assessment is perfectly in line with what required by the ISO standard in the goal and scope phase (ISO 2006). However, this proved not to be sufficient to properly address and model the problem.

Table 1 Examples of questions addressed by means of CLCA

Reference	Subject	Question addressed/purpose of the study	Consequence(s) addressed	Target audience
Dalgaard et al. (2008)	Soybean meal	To establish a reliable representation of soybean meal production for use in LCAs of European livestock production chains To estimate the environmental consequences of soybean meal consumption using a consequential LCA approach To identify the environmental hotspots in the product chain of soybean meal	The increased production of soybean meal affects the palm oil and rapeseed oil production, respectively (soybean-rapeseed loop)[a]	Not explicitly addressed. The results have two main potential users: Scientific community (availability of data about for LCA on livestock products) Decision makers at national level, since the information of the study can be used to set policies for the sector
Gamage et al. (2008)	Furniture (chair)	To determine the environmental hotspots in the life cycle of two chairs To compare the life cycle impacts of the two chairs To compare alternative potential waste management scenarios	None. The study is indeed an attributional one, even if the authors classify it as consequential	Producers and designers working in the furniture sectors
Gaudreault et al. (2010)	Pulp and paper mill	To compare the information provided by ALCA and CLCA approaches for decision-making regarding the selection of process options aiming at reducing the dependency of an integrated newsprint mill to purchased electrical power	Consequences identified for each of the four options considered (increase in cogeneration capacity and of the DIP [b] content of the paper) Reduction of recycled pulp production in other systems due to an increased use of recycled paper is compensated by an increase in a mixture of virgin kraft and TMP[c] pulp New consumption of virgin fibre results in additional extracted material Decreased use of wood chips (due to the implementation of the four options) leads to less material to be disposed of Reduction of electricity consumption (due to the implementation of the options): coal fuelled power plant is identified as marginal technology for electricity	North America pulp and paper mill managers
Lesage et al. (2007a, b)	Brownfield rehabilitation	To evaluate the potential environmental impact associated with a brownfield rehabilitation project aiming at residential redevelopment	Three categories of consequences are analysed: Primary: changes in the site's environmental quality Secondary: changes due to the rehabilitation service system (supply of housing services)	Not explicitly defined. However, the optimal target audience is represented by decision makers operating at a territorial level (those who are in charge of the management of brownfield)

Table 1 (continued)

Reference	Subject	Question addressed/purpose of the study	Consequence(s) addressed	Target audience
			Tertiary: effects of the reoccupation of the site on the life cycle of other regional sites (inclusion in the analysis of other site occupations marginally affected by the increase in supply of housing services)	
Nielsen et al. (2007)	Enzyme products	To address the environmental impact potentials associated with enzyme production in a cradle-to-gate perspective	Displacement of alternative sources of N and P fertilisers as a result of the enzyme application in agriculture Starch applied in enzyme production has protein (gluten) as co-product. It is assumed that the marginal protein displaces other types of protein for animal feed Natural gas fired power plant is the marginal source of electricity identified in the study	The company that produces the product investigated in the study
Nielsen and Hoier (2009)	Mozzarella cheese production	To assess the environmental impacts that come with the use of industrial phospholipase in mozzarella production and compare these with the savings that come with the avoided milk production	Increased demand for vegetable oil (palm oil) as a result of the reduced output of fat from the mozzarella production of the edible fat market Increased demand for alternative protein sources in animal breeding (soybean meal) as a result of the reduced protein output from the cheese factory	The company that produces the product investigated in the study
Skals et al. (2008)	Enzymes	To investigate whether the enzyme technology is a more environmentally sound alternative than the conventional ways of producing paper	Not discussed in detail. Reference is made to the inclusion of changes occurred when enzymatic solutions displace conventional solutions but evidence is not given. Only the following aspects have been included: Natural gas and coal were selected as marginal sources of electricity	The company that produces the product investigated in the study
Thomassen et al. (2008)	Milk	To demonstrate and compare the ALCA and CLCA of an average conventional milk production system in the Netherlands	Natural gas power plant is identified as the marginal source of electricity Soybean meal was identified as the marginal fodder protein (being the feed ingredient that will meet the increased protein demand due to increased milk production)	Policy makers

[a] Soybean oil is the co-product of soybean meal. The avoided production of other vegetable oils (rapeseed, palm), caused by the production of soybean oil, is included. Because vegetable oil is co-produced with protein, this introduces another need for system expansion (which again includes a co-production of protein).

[b] DIP is the short for deinked pulp. It is recycled paper which has been processed by chemicals, thus removing printing inks and other unwanted elements and freeing the paper fibres.

[c] TMP stands for thermomechanical pulping

Table 2 Application of CLCA to case studies about biofuels/bioenergy

Reference	Subject	Question addressed/purpose of the study	Consequence(s) addressed	Target audience
Lemoine et al. (2010)	Bioenergy	To examine the relative climatic merits of combusting corn grain or switchgrass for electricity generation versus refining corn grain or switchgrass To produce liquid fuels for use in the current vehicle fleet	Detailed discussion about the displaced source of electricity when an increase in bioelectricity occur. Parameters analysed: type of electricity replaced and structure of the regional electricity market	Policy makers
Lim and Lee (2011)	Palm oil biofuel	To determine the environmental consequences of the inclusion of second-generation biofuels (bioethanol from palm oil biomass) towards current palm oil biodiesel production	Not clearly identified and discussed Increased use of inorganic fertilisers to replace the removal of palm oil fronds Replacement of palm oil fibre and shell by fossil fuel as team-boiler fuel	Not clearly defined
Reinhard and Zah (2009)	Cassava	To assess the direct and indirect environmental impacts to be expected if Switzerland should replace 1% of its current diesel consumption with imports of soybean methyl ester (SME) from Brazil, or palm methyl ester (PME) from Malaysia	Several mechanisms and consequences taken into account: The effects of an increased demand for a specific crop on the agricultural stage are assumed to be met by expansion The identification of the increased production of the marginal vegetable oil on the world market when the use of soybean oil for biofuel production increases The identification of the substituted for the protein source (for animal fodder) when palm kernel meal increases as a consequence of increased production of palm oil for biofuels	Not specified, but it is assumed to be represented by policy makers and implementers of biofuels policy
Silalertruksa et al. (2009)	Cassava	To identify the environmental consequences of possible (future) changes in agricultural production systems and determine their effects on land use change and GHG implications when cassava demand in Thailand increases	Changes in the region where energy crop demand increased: Consequences due to the conversion of unoccupied land to cropland Increased production by yield improvements in the country Displacement of cultivated area of other crop (sugarcane) in the country and reduced sugar production is compensated by yield improve or increased cultivation in other countries Changes in other regions:	Policy makers and implementers of biofuels policy

Table 2 (continued)

Reference	Subject	Question addressed/purpose of the study	Consequence(s) addressed	Target audience
			Increased demand is met by import from other countries Reduced sugar products in the market are compensated by increased production in another country	
Smyth and Murphy (2011)	Grass biomethane	Identification of the likely indirect effects of a grass biomethane industry in Ireland as a reduction in beef exports to UK	A detailed analysis of consequences is provided: UK demand for beef is unchanged and reduction in Irish import is met with an increased UK beef production Unchanged UK beef demand but increase in beef imports from other countries to meet the demand Decline in UK consumption met by the consumption of poultry	Not discussed, but the target is represented byPolicy makers and implementers of biofuels policy

Examples of questions addressed and consequences analysed

Tillman 2000; Weidema 2003; Weidema et al. 2009), some authors further elaborated on the concept, giving interpretations that do not always reflect the expressed intentions of the primary authors. Some authors associate the concept of consequential only to the way in which multi-functionality is dealt with (Gamage et al. 2008; Gaudreault et al. 2010), and thus system expansion is considered a synonym of CLCA. One may refer to these studies as semi-CLCA (cf. Schmidt 2010). In a similar way, others make reference to a consequential approach to system delimitation (Lim and Lee 2011), but the study they carried out is actually an attributional one, in which no consequences are addressed. Overall, interpretations on CLCA range from considering it as the state-of-the-art methodology, to just a complication, and finally, to a model that avoids allocation by means of system expansion.

These misalignments point out that the choice of CLCA versus other modes of LCA is not always done consciously, and the consequences are propagated at the level of modelling, as described in Section 3. This in turn reaffirms the fundamental importance of the goal and scope phase in unambiguously defining what the LCA study is about and for whom it is intended. In fact, the depth and the breadth of LCA can differ considerably depending on the goal and scope of a particular LCA, and errors made in this phase may have strong consequences for the results (Fullana et al. 2011).

3 "What"—methodological content of CLCA

After the analysis of the CLCA applications, the review focused on the modelling technique. The purpose was to identify the main characteristics of the approach, possible shortcomings in the current applications, and areas for improvements. We started out by examining the nature of modelling and then focused our attention on one of the most characteristic aspects of CLCA, namely the choice of affected processes.

3.1 The nature of modelling

Discussing the nature of modelling means analysing principles, analytical techniques used and their limitations, all characteristics that define what the model can (and cannot) do, and thus contribute to the identification of how to solve the problem at hand. To our knowledge, these aspects have not been dealt with in detail in the literature, with the exception of Weidema et al. (2009, p. 7) who define CLCA as a "steady-state, linear, homogeneous model, with each unit process fixed at a specific point in time". From this point of view, no differences exist with respect to ALCA. The application of CLCA is not time-related, as already

discussed in previous publications (e.g. Curran et al. 2005; EC JRC-IES 2010; Sandén and Karlström 2007) and thus both the adjective "retrospective" and "prospective" apply. Time is a parameter outside the models in both cases, but this simplification seems to be less acceptable, at least at a conceptual level for CLCA. In fact, the term "consequential" suggests that, since the primary object of the model is the analysis of consequences, there is a sequence in time of events that gives rise to a propagation effect, according to which the consequence at time t_1 is different from that at time t_2.

However, in CLCA we are interested in two main aspects from the temporal point of view: the end time of consequences (t_1, t_2, …, t_n) and the storyline on how to arrive at that point. Then, CLCA is defined for a given point in time, and at that point, the changes occurred are modelled in a steady-state way, using the information given by the storyline.

According to Weidema et al. (1999), this is still done under the ceteris paribus assumption (CPA), because the changes analysed are usually small compared to the production in society, which can be assumed to be unaffected.

Considering that ALCA and CLCA share the same modelling principles, what distinguishes CLCA from ALCA? We tried to answer this question by making reference to the general modelling principles discussed by Heijungs et al. (2007), namely the distinction between a system and its environment (*where boundaries are set*), the internal structure of a system in terms of its components (*unit processes and environmental compartments*), the relationships among the components, and the relationship between the system and its environment (*open* versus *closed* versus *isolated system*). With respect to the principles introduced above, the main distinctive characteristics of CLCA compared to ALCA are (Weidema 2003):

(a) Processes are included to the extent of their expected change caused by a demand (affected processes).
(b) Co-products are handled by system expansion.

Regarding the first aspect, the inclusion of affected processes represents an attempt to include market mechanisms into the analysis. In fact, processes are selected on the basis of considerations on how the market of the system investigated might look under the hypothesis of the change analysed, introducing insights into the future. We should be aware that these "future" considerations are not a peculiarity of CLCA but can be dealt with also in other LCA modes, making the assessment prospective (Spielmann et al. 2005), or elaborating scenarios (Sandén and Karlström 2007), trying to understand what the situation in the future will look like, with or without taking the change in demand into account. However, since the main difference between CLCA and other LCAs relies on the choice of processes to be included in the system, their representativeness and relevance with respect to the changes that occur is a daunting question. Presently, the underlying assumption in CLCA studies is that technological data are the same: some new/future technologies are assumed, but current processes are used to represent them. This assumption can be less relevant for short-term changes, but when long-term changes are involved, data projections are probably needed.

As far as the other distinctive characteristic of CLCA is concerned, we did not analyse how system expansion has been applied in the several case studies, since the question of multi-functionality has been the object of several publications. We would like to point out only the connection between the boundary expansion and how the functional unit (FU) is dealt with in CLCA. According to the several definitions provided in the literature in CLCA, the boundaries of the system are expanded so as to include those processes which are affected by the consequences of the decision at hand. In doing so, the resulting FU of the whole system would consist of multiple functions, including the main system and those added by the processes included in the boundaries. When a comparative analysis has to be conducted, it might be difficult to guarantee the functional equivalency between the systems compared, since the processes included in the two situations might serve different functions. Moreover, such a resulting *multi* FU raises some concerns about whether it can still be considered a FU. The question is not addressed in the literature, with the exception of Smyth and Murphy (2009) in relation to the comparability problem due to the different boundary conditions. Even Weidema et al. (2009) state that when small changes and consequences are at the core of CLCA, further requirements on FU are not necessary. Moreover, the authors pointed out the relevance of the FU only in terms of "quantity" (it should "reflect the extent of the consequences of the decisions studied", when decisions "involve the entire market of a major product or process", as stated by Weidema et al. (2009), p. 22) and not "number of functions".

How to deal with a *multi* FU and how this affects modelling is an aspect which requires more understanding and research, which could also help in the development of CLCA modelling.

3.2 Identification of affected processes: where do we set boundaries?

As already pointed out above, one of the main issues of CLCA is the identification of the processes to be included in the analysed system, which implies the way in which boundaries are set. In this regard, the methodology is clear in stating that only (but all relevant) affected processes need to be included, defined as those that respond to changes in demand and/or supply driven by the decision at hand. However, a decision can affect processes through a wide

range of mechanisms, which cause different consequences. For example, a change in demand and/or supply may influence prices that determine what is produced (substitution mechanisms) and who can afford to consume it (income effects). Price changes in turn affect income to an extent that depends on how large the cost of the item is relative to the consumer's budget. Rebound effects or ripple effects, as defined by Hertwich (2005), might then occur when, for example, the increased real income due to the reduced price of a good causes consumers to increase their demand for other goods (see also Girod et al. 2010). The chain of consequences that can be analysed does not seem to have an end. However, not all of these consequences are presently taken into account in CLCA (for example, a few approaches to rebound effects still exist—see Thiesen et al. 2008), and simplifications are adopted, for example, in relation to the number of markets dealt with simultaneously, to the scale of the consequences,[4] or to the complexity of substitution mechanisms, as can be seen in the examples of Tables 1 and 2. In fact, usually only one market situation is modelled and only one affected process/technology is identified. Other approximations refer to the investigation of a stand-alone increase in demand, assuming that substitution occurs within the same type of products (Schmidt 2008). This is clearly a limitation, because products and markets are connected, and an increased supply of some products implies increased demand for upstream intermediate products (Lundie et al. 2008). In some cases, as extensively discussed by Earles and Halog (2011), attempts to link several markets simultaneously have been made using partial equilibrium models (PEM) or general equilibrium models (e.g. Dandres et al. 2011; Ekvall and Andrae 2006; Kløverpris et al. 2008; Kløverpris et al. 2010; Lesage et al. 2007a, b). The studies carried out demonstrate that the use of PEM is limited by the knowledge of the price elasticities, adding great uncertainty to the model. There is also the problem that PEM can be modelled only for a few markets, and the decision regarding which markets to include needs accumulated experience. Moreover, PEMs ignore interactions between markets, while in real world, substitution involves cross-elasticities, being the change in demand/supply for one good in response to a change in the price of another good.

A procedure to support the identification of the affected processes, which had been developed since 1999 (Weidema et al. 1999), was updated and refined in 2009 (Weidema et al. 2009). That procedure consists of five steps, during which the following elements are analysed: (a) the time horizon of the study; (b) the analysis of the extent to which the changes in production volume only affect specific processes or a market; (c) the trend in the volume of the affected market; (d) the analysis of the extent to which the technology has the potential to provide the required capacity adjustment; (e) the analysis of whether the identified technology is the most/least preferred. The procedure is schematised into a decision tree which guides the practitioners throughout all the steps.

Moreover, recently Schmidt (2008) also developed a procedure for system delimitation in agricultural CLCA. However, the identification of affected processes in case studies (e.g. Lemoine et al. 2010; Nielsen et al. 2007; Skals et al. 2008) is still often done without adopting the procedures developed, using various arguments not always supported by the evidence of market information. Moreover, even when the procedure is applied, evidence is not often given in the papers. Some authors simply use the results of previous studies without providing arguments in support. For example, in several studies involving vegetable oils (e.g. Dalgaard et al. 2008; Nguyen et al. 2010; Nielsen et al. 2008; Nielsen and Hoier 2009; Thomassen et al. 2008), the results obtained by Schmidt and Weidema (2008) have largely been adopted, without justifying the full consistency with and appropriateness for the specific case at hand. This attitude has been pointed out recently by Reinhard (2011) who stressed how results cannot be generalised or used for similar or relating goals and scope. In other cases, dynamic optimising models have been applied (Eriksson et al. 2007; Mattsson et al. 2003), together with energy system analysis simulation tools (Lund et al. 2010; Mathiesen et al. 2009), which demonstrate that a set of affected technologies, instead of just one, can provide a more complete description of the consequences.

Mathiesen et al. (2009) tested the ability of identifying marginal electricity technologies in CLCA by analysing the statistics of historical developments of the energy system. The results show a discrepancy between the energy technologies identified as marginal in the LCA studies and the actual marginal electricity technologies. The authors demonstrated that marginal energy technologies are identified inconsistently, using different arguments, and not always mentioning market trends.

These discrepancies between the actual and the foreseen marginal energy technologies, which could probably be identified also for other technologies, are partly unavoidable when modelling the future, but might also be partly due to erroneous assumptions and simplifications adopted in modelling the market consequences. Moreover, it is not clear if the wrong identification of the affected processes should be ascribed to an inappropriate application of Weidema's recommended procedure or to the individual choices made by

[4] Typically the scale of the potential changes is small (for non-marginal variations see the work of Dandres et al. 2011), which means the direction of the trend in market volume and the constraints on and production costs of involved products and technologies are not affected (Weidema et al. 2009).

practitioners, seldom transparently documented. There is a high degree of uncertainty and a wide range of possible results, depending on the system enlargements (and thus on the affected processes taken into account), on the type of indirect effects included, and on the assumptions and scenarios made (Eriksson et al. 2007; Nielsen and Hoier 2009; Reinhard and Zah 2009; Schmidt 2010; Smyth and Murphy 2011). Thus, where boundaries of the system should be properly set is a tricky question. Without making the definition of the system boundary a rigid procedure but flexible enough to account for the potential impacts of a change in production demand, the need exist to define procedures and rules to increase the robustness of the studies. In this regard, sensitivity analysis and the use of scenarios are unavoidable (Mathiesen et al. 2009). The two techniques together can contribute to considering how the consequences might change under several market situations, taking into account relevant parameters to calculate substitution, the possible marginal products on the world market, and the feedback mechanisms (Reinhard and Zah 2009).

4 Discussion

In the previous sections, it has been clarified that the introduction of (some) market mechanisms in the analysis, throughout the inclusion of the affected processes in the product system, is what primarily distinguishes CLCA from other modes of LCA.[5] The logic behind this is that all products are included in markets, with price mechanisms, among other factors, regulating their production, development, and consumption. Thus, the common supply and demand mechanisms introduce perturbations in the system that reacts accordingly, giving rise to a chain of cause–effect relationships. These market relations or mechanisms are presently not endogenised in the model (Lundie et al. 2008), but are derived from economic models (e.g. Dalgaard et al. 2008; Eriksson et al. 2007; Lemoine et al. 2010; Lesage et al. 2007a, b; Lund et al. 2010; Pehnt et al. 2008) or outlooks in specific sectors (e.g. Schmidt 2010; Schmidt and Weidema 2008), and then included as input into LCA.

One could argue that even market mechanisms are not a key characteristic of CLCA because the substitution or avoided-burden method for handling multi-functionality already adopts inclusion of market mechanisms as basis for "avoiding" allocation in ALCA, and prices can be the basis of allocation in ALCA. However, the way in which multi-functionality is handled is just one component of CLCA (semi-CLCA), which also entails the methodological implications discussed above.

The inclusion of market mechanisms and information into LCA has been strongly criticised in a recent paper by Pelletier and Tyedmers (2011), who consider market signals inadequate in managing the environmental dimensions of activities. With reference to CLCA, they state that since the purpose of CLCA is "to model impacts that result as a consequence of decisions, as mediated through biophysically myopic market transactions, the utility of resultant research outcomes is similarly questionable" (Pelletier and Tyedmers 2011, p. 9). However, this conservative position neglects the economic and ecological interdependencies, which have already been identified as one of the causes of policy failure in both environmental and economic development (Bartelmus 2008). If from the one side we could agree on market aspects being inadequate to catch environmental issues, on the other side we have to recognise that if we want the foreseen system changes to be reliable, we should base them on mechanisms of actual markets. Moreover, the inclusion of market mechanism would add realism (i.e. accuracy) to the analysis, which is the ultimate goal of any model. Clearly, the system complexity will be higher because CLCA includes additional economic concepts such as marginal production costs, elasticity of supply and demand, and so forth. Some models used in the analysis are also much less transparent than the linear and static/steady-state model of a traditional LCA. Their results can also be very sensitive to assumptions. This all adds to the risk that inadequate assumptions or other errors significantly affect the final results (Ekvall and Andrae 2006; Gaudreault et al. 2010; Reinhard and Zah 2009; Schmidt 2010; Smyth and Murphy 2011). However, the complexity and uncertainty, on the one side, can be balanced with the dramatic increase in knowledge about the system on the other (Lesage et al. 2007b; Schmidt 2010; Silalertruska et al. 2009), a compromise that can be accepted if the analysis is transparent in the assumptions and choices made regarding the different consequences considered.

The logic of mechanisms could be the reading guide for better understanding and further developing CLCA. The modelling specification in terms of which market mechanisms are included in the analysis can provide better indications than the term "consequential" itself.

Going further, this logic could be extended, considering CLCA and the other modes which address changes (BLCA, DLCA) as approaches—and not modelling principles with defined rules—to deepen LCA, to include mechanisms that result from an initial change to some parts of the product system. Which mechanisms to include is a tricky question, since they can show up everywhere, involving a variety of domains. Market mechanisms are part of broader economic mechanisms, which recall concepts like employment and

[5] Presently LCA includes only technological and environmental relations in the inventory and impact assessment phase, respectively (Heijungs et al. 2010).

growth. These in turn function within a cultural, social, political and regulatory context. This process of adding mechanisms would require that those constraints typically assumed as fixed entities[6] under the present modelling are taken into considerations, relaxing the ceteris paribus assumption related to both temporal and causal aspects.[7]

Specifying which constraints to impose and why, which to relax (e.g. change in functional unit, change in technology, constrained capacity, market reactions, production volume developments, etc.), whether all together or just one by one, and which (market) mechanisms to include and how to report them, would support the introduction of more mechanisms into the analysis and contribute to making the assessment more consistent and robust.

Someone could argue that the distinction among the different modes of LCA is in contrast with the suggestion of considering CLCA as an approach rather than a modelling technique. In fact, if a practitioner is asking the right question, the resulting LCA should be designed to answer that question, regardless of how we call it (ALCA, CLCA, DLCA, BLCA). However, CLCA at this stage of development still does not have all the capabilities for addressing all the mechanisms, and thus it distinguishes itself mainly for being a modelling technique with defined rules. In this context, it is important to provide practitioners with detailed guidance on a number of issues, including: how to select the most appropriate data; how to deal with multi-functionality; how to identify the mechanisms to be modelled and the affected processes to be included in the system boundaries. In this regard, an interesting support to address both present mechanisms and future developments could be provided by scenario modelling, as suggested also by Mathiesen et al. (2009). Frameworks for scenario development in LCA have already been developed, and can be found in Pesonen et al. (2000), Fukushima and Hirao (2002) and Spielmann et al. (2005). Börjeson et al. (2006) further detailed the approach of Pesonen et al. (2000), by proposing a scheme in which three main categories of scenarios are distinguished, namely predictive (what will happen?), explorative (what can happen?), and normative (how can a specific target be reached?). Each contains two scenario types respectively: Forecast and What-if, External and Strategic, and Preserving and Transforming. A clear identification of which type of scenarios is most appropriate for CLCA is difficult since there is a grey area between the different categories, especially between what-if scenarios and explorative scenarios, as pointed out by Börjeson et al. (2006). On the one hand, what-if scenarios would support the investigation of what will happen on the condition of some specified events in the future. Some case studies on CLCA reflect this logic (see, for example, Schmidt 2010). On the other hand, explorative scenarios, "staying to the facts" (Heijungs and Guinée 2007), explore situations and developments that are considered possible to happen. Moreover, they are elaborated with a long time horizon to allow for more profound changes, and accordingly, the long-term is considered the typical dominant effect in CLCA (Weidema et al. 2009), even if evidence is not always given in the case studies (for example, Schmidt (2010) considers only 5–10 years ahead, while most of the authors do not specify the time perspective adopted).

Thus, both scenarios can support CLCA in providing a more scientifically sound basis to model specific product-related futures with respect to technology development, market shifts, and so forth. In fact, scenarios could be used to frame the questions, before the system is modelled by means of the inclusion of mechanisms, and a representation of possible future alternatives is obtained. Such a structured and extended analysis would make it possible to address the several dimensions involved in any assessment, like time, the size of change, and the size of consequences, just to cite a few.

5 Conclusions and recommendations

CLCA has been applied for many years, but has only recently gained momentum in being applied for evaluating the environmental consequences of an action/decision into consideration in different disciplinary fields, also outside the domain of LCA. However, despite the numerous methodological papers published on the topic and the increasing number of applications, we have come to the conclusion that the CLCA is still far from a proper systematization. In fact, our analysis points out that the application of the consequential modelling is often done in a non-systematic and inconsistent way, suggesting that CLCA is still not fully understood either at a conceptual or at a modelling level. CLCA seems to be considered as a macro container in which different concepts flow in, not always mutually consistent in terms of the perspective adopted (prospective/retrospective), the direction in time (future/past), the typology of consequences analysed, and the effects included (marginal versus average). Overall, considering how CLCA is perceived and applied by practitioners, it appears that there are more

[6] Constraints can be technical, political, natural, and marked-related. A common simplification adopted in CLCA is to consider them as fixed entities due to the difficulties in modelling them. Thus, it is assumed that they do not change, even when the long-term horizon is analysed.

[7] The CPA, assuming away any interference from the system, works under the hypothesis of isolation. The temporal isolation assumes that those factors we consider frozen under the CPA move so slowly relative to the others that can be considered constant at any point in time. The causal isolation considers that the same factors are not significantly affected by the processes under study. Thus, the more the mechanisms are added, the more the CPA and its related constraints are relaxed, the more the steady-state and static models become tight because causes and effects are always intertwined in time.

shadows than lights in CLCA. The result is a lack of clarity about *what* CLCA is, *for what* it is useful, and *what it entails* from the methodological point of view.

Regarding the *what* question, our analysis points out that CLCA stands out as a modelling approach that takes (some) market mechanisms into account. We propose to use the logic of mechanisms as a good criterion for distinguishing between CLCA and the other modes of LCA. On the *modelling* side, while ALCA and CLCA share the same modelling principles, the main difference between them relies on the way in which the boundaries of the system are set and the processes to be included are selected. Which types of processes, and thus, which type of causal chains should be included and how to identify them are the main questions, which are dealt with differently and not always transparently by practitioners, leading to different results.

We suggest that scenario modelling could provide an important contribution to better structuring CLCA. In fact, it can increase the robustness of studies by providing an approach to think about plausible future developments in a structured manner (Zurek and Henrichs 2007). Moreover, in doing so, they also support the identification of relevant mechanisms to be included in the analysis. However, as data uncertainty can be very large in scenarios that refer to technologies not yet in use, accounting for future developments increases the need for methods to manage great uncertainties (Höjer et al. 2008).

As far as the *what for* is concerned, the analysis highlights that this aspect is not well addressed at the methodological or practical level, despite its relevance. The correct formulation of a question is central in every evaluation, but its importance continues to be neglected. We believe that the lack of attention to this important aspect is at the origin of the dispute between CLCA and the other modes or types of LCA over the last 20 years, and consequently, of the lack of clarity about the contexts in which CLCA could be applied. How to better link questions and models is an important field of research, not only for CLCA, and it requires the development of practical guidelines on how to frame questions, to identify what the problem to be tackled is exactly, what the derived questions are, what the technological options are, what the scale of the expected changes is, what the time frame of the question is, if a ceteris paribus assumption may hold, if the system analysed is replacing another system at a small scale, or if the technology used in the new system is expected to extend to many more applications on a larger scale (Guinée et al. 2009). It is the sum of all these answers that determines which methodological choices are relevant, and thus, which mode is most appropriate.

Besides framing the question, further efforts should be devoted to improve the existing approach, which is considered to still be in its earliest stages (Anex and Lifset 2009), and making it a robust support to decisions with long-term consequences (see, for example, the Renewable Fuel Standard programme developed by US-EPA, in which the use of CLCA for GHG emissions accounting is required). Efforts are necessary to clarify when and which market information is important, to improve long-term forecasting techniques, and to identify the affected processes.

However, together with shadows we believe that there are also many lights in CLCA, three in particular which we would like to point out. The first refers to the fact that CLCA forces practitioners to think about the correct formulation of a question. Since consequences are at the core of CLCA, we need to explicitly state them in the research question in order to identify which processes to include in the analysis and thus how to set boundary. Thus, it is thanks to CLCA that the topic of framing the question gained again its importance. The second aspect is the ability of CLCA to model some economic mechanisms. Despite the several methodological developments still needed and highlighted above, CLCA provides an important sophistication of the LCA methodology. It adds the capability of accounting for those linkages, pointed out by Graedel and van der Voet (2010), which are inherent in any sustainability evaluations. Building upon this concept, we arrive at the third positive aspect, that is the perspective offered by CLCA. We suggest that the concept of CLCA could be broadened (extended CLCA) so as to be considered as an approach—rather than a modelling principle with defined rules—to deepen LCA, providing the conceptual basis for including more mechanisms than the market ones.

In conclusion, scenario and modelling of mechanisms, together with framing the question, are three important research fields for CLCA that deserve attention, since they could be seen as the backbone of any assessment.

Acknowledgements This research was partially funded by the Italian Ministry for Education, University and Research-MIUR, with the support of the LECOP LABORATORY of Emilia-Romagna High Technology Network and the EU-FP7 Sustaining Ethical Aquaculture Trade (SEAT) project.

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